> ***Competency 1.6*** **Radiation protection personnel shall demonstrate a working level knowledge of internal and external radiation protection principles and control techniques.**

1. SUPPORTING KNOWLEDGE AND/OR SKILLS

a. Discuss the implication of the following on the identification of hazards associated with radiological work activities and how it might affect the controls specified on a radiation work permit (RWP):

- Location of the work (i.e., in a radiation, contaminated, or airborne area)
- System being worked on (i.e., fluid under pressure, hazardous or radioactive)
- Nature of the work activity (inspection, opening system, etc.)

b. Discuss special exposure control, survey and personnel monitoring techniques associated with work in the following areas or situations:

- Nonuniform radiation fields
- High radiation areas
- Contact work with radioactive materials/sources

c. Discuss the hierarchy of controls used to prevent uptakes of radioactive material by personnel, and potential worker hazards associated with implementation of these controls.

d. For a radiological incident (i.e., spill, loss of containment), discuss the potential and magnitude of the following:

- Loose surface contamination levels
- Airborne radioactivity levels

e. Discuss appropriate personal protective equipment (including respiratory protection) for subsequent entry into, and decontamination of, the above area.

f. Using reference material and given the activity, calculate radiation levels from a point, line, and plane source.

g. Given buildup factors and half-value layers, perform shielding calculations.

2. SUMMARY

Radiation Work Permit (RWP) Controls

Radiation work permits (RWPs) are an administrative tool used to control work in radiological areas, authorize and maintain exposures as low as is reasonably achievable (ALARA). RWPs represent one of the primary administrative controls by which radiological work is planned and radiation worker safety is addressed. In addition, RWPs provide a means to trend radiation exposure by specific work activity, plant system and work location.

<u>Work Location</u>

Identifying the work location is important in order to write the RWP, conduct pre job briefings, and maintain exposures ALARA. In order to plan work in radiological areas, surveys must be taken at the work location to determine the radiological hazard(s) present. Once the radiological hazard(s) have been identified, radiation protection personnel write the RWP specifying the radiation protection precautions based on the radiological hazards in the area, the system on which work is being done, the type of work performed, and the potential for hazard(s) to occur.

Once the RWP is written and prior to the commencement of work, a prejob briefing is usually conducted to inform the workers of the exact location of work to be performed, scope of work, radiological conditions, and precautionary measures.

Reducing time in a radiation area minimizes dose. Workers must know the exact location of work to minimize the time spent in the area. For example, due to a lack of a prejob briefing identifying the work location, workers may search for the work area, increasing time spent and possibly entering higher than necessary radiation fields resulting in greater doses. Also, radiation fields can vary drastically with distance and small changes in worker position can alter doses received by workers.

The assessment of the radiological history of a work location is also important. When determining the location of work, technicians should include an assessment of accessible contamination and radiation levels, hot spots, and history of spills in the area. An example of a radiological hazard, due to insufficient assessment of work location, happened in the Fall of 1996 at the B-Plant Hanford, WA:

> A job involving a replacement of a flange, with a blank flange from an uncontaminated system, was assigned. The area was posted radiological buffer area for contamination control. The available survey data on the flange and adjacent area indicated loose surface contamination, the detector readings were on the order of 30 mrad/hr. The history of the area was not taken into consideration during the development of the RWP and work package. Unbeknownst to workers, a serious radiological spill, predominately strontium-90 (Sr-90), had taken place in that area in the past; the residual contamination was convered with lead and paint. The 30 mrad/hr levels on the flange indicated significant contamination fixed into the paint, with the potential for loose surface

contamination underneath and in the flange crevices. Radiological control personnel erroneously determined no radiological controls were required, except for swipes on opening the flange as a precaution. Millions of dpm/100 cm^2 were found on opening the flange and a spread of contamination occured due to inadequate radiological controls.

Systems Under Maintenance

The systems to be worked on need to be clearly identified to ensure work is preformed on the correct system, maintain worker safety and ALARA. Systems should be locked and tagged out to help identify them as the correct system. Working on the wrong system wastes time, which increases dose, can result in a hazardous situation, and jeopardizes plant operation.   Many plant systems are pressurized and upon opening can spray radioactive liquid, mist or particles, onto unprepared workers. Uncontrolled depressurization can result in nonradioactive hazards such as the release of projectiles, steam, and/or hazardous materials.

The radiological hazards associated with a system include the isotopes of concern (i.e., plutonium nitrate, dissolved spent fuel, purified water with residual tritium, etc.) Isotopes have distinct differences in radiological hazard that contribute to risk and thus appropriate levels of control.

How contaminated is the system at the point being accessed?

- A system containing feed material, such as dissolved spent fuel, has a higher level of risk than an interfacing system that may feed pure water into the contaminated system. These interfacing systems get cross-contaminated to varying levels depending on the location and types of backflow preventors installed and depending on history of operational problems that resulted in cross-contamination.

- Secondary plants may have low-level contamination due to primary to secondary leaks.

- A high efficiency particulate air (HEPA) filtered ventilation system has a greater radiological hazard upstream of the HEPA as compared to downstream, and so forth.

Depending on the isotope (e.g., strontium-90 [Sr-90] versus cesium-137 [Cs-137], radiation survey data on the outside of the system can provide an indication of internal contamination levels.

- An understanding of the system allows engineering analysis of the potential for radioactive liquids to be discharged on breakthrough of the system. Controls such as blowdown of liquids, installation of freeze seals, installation of glove bag with radioactive liquid collection bottle, etc. are evaluated based on knowledge of the system.

- Surveys are performed for interfacing systems to release the clean portion of the system from radiological control.

- Neutron activation of system components. Another aspect of radiological hazard associated with a system is the potential for activation of some components from neutron flux.

Work Activity

Knowing the nature of the work activities is important in prescribing radiological protective measures. In many cases radiological hazards, such as surface or airborne contamination, are present inside systems or components which cannot be surveyed prior to the start of work. Under these conditions, radiological precautionary measures need to be based on the scope of work. For example, the area outside the component may be clean, but upon system opening will become contaminated due to internal system contamination, so the work area may need to be set up as contaminated prior to work. Another example is the production of airborne radioactivity due to excessive surface contamination inside systems. Airborne radioactivity levels may be insignificant before system opening, but work activities may generate airborne contamination due to welding, grinding, sanding, evaporation, chemical volatility or worker movements.

Field Surveys

Nonuniform Radiation Fields

Radiation fields can be very localized or broad depending on the size, geometry, or distribution of the radiation source; shielding effects; or distance from the source. In many work situations, the radiation field intensities can vary greatly from head to foot or back to chest. Problems occur when the individual's dosimetry is not placed in the highest whole-body radiation field. Under such conditions, the dosimetry would not record a dose that is representative of the individual,s whole body dose. Take, for example, a small point source located above an individual,s head causing a radiation fields of 100 mrem/hr at the head, 40 mrem/hr at the chest, 20 mrem/hr at the waist and 10 mrem/hr at the knees. If the individual were required to work in this area for three hours, standing in the same position, the dosimetry, usually worn on the chest, would not reflect the highest whole- body dose which would be to the head.

According to the *Radiological Control Manual*, Article 512.5:

> "Multiple dosimetry should be issued to personnel to assess whole-body exposure in nonuniform radiation fields or as required on RWPs. Nonuniform radiation fields exist when the dose to a portion of the whole body will exceed the dose to the primary dosimeter by more than 50% and the anticipated whole-body dose is greater than 100 rem. The technical basis document should describe the methodology used in determining the dose of record when multiple dosimeters are used."

Because of the weighting factors of the various body parts, alternate locations, such as the head when weighted, contribute significantly less to the total dose than to the trunk dose. Common locations for placement of multiple dosimetry include the head, chest, back, gonads, top of the arms and legs.

Nonuniform radiation fields are identified by scanning the work area with the radiation survey instrument to locate the source of the radiation fields and noting the change in readings as the instrument is moved to the head, chest, and thigh regions. Nonuniform radiation fields also result from the source and/or workers changing positions. Gradient radiation surveys and consideration of body positioning in the gradient is useful for nonuniform radiation fields. A gradient radiation survey is a three-dimensional survey, where the maximum radiation dose rate in the grid is identified on the survey map.

Neutron monitoring requires special concerns. Albedo dosimeters require the hydrogenous body behind it, and multibadging of the head would be impractical.

High-Radiation Fields

Access to high-radiation areas are controlled by both administrative and physical controls. Administrative controls include procedures requiring an RWP and personnel dosimetry for entry into high-radiation areas. The *Radiological Control Manual*, in Article 513, outlines the detailed procedures for issuing supplemental dosimeters, which must be issued upon entry into high- or very high-radiation fields. Electronic dosimetry can be set to alarm at preset doses and dose rates alerting the individual to leave the area or take other corrective measures. In many cases, RWPs for high-radiation area entries require the individual to carry radiation survey instrumentation. In some cases, the placement of dosimetry on the body will also be specified.

Physical control can include locked doors, gates or fences to control inadvertent access. Radiation protection personnel control the access to high-radiation areas; issuing keys only if the person has proper training, has a valid reason for entry, and is signed in on the appropriate RWP. Additional means to control inadvertent entry are by radiation postings, rope, and barriers.

Regulations covering entry into radiological areas are governed by 10 CFR 835, Subpart F. They include one or more of the following methods to ensure access control:

(1) Signs and barricades

(2) Control devices on entrances

(3) Conspicuous visual and/or audible alarms

(4) Locked entrance ways

(5) Administrative controls

Access to high- and very high-radiation areas (> 1R/hr) are controlled by one or more of the following:

(1) A control device that prevents entry or reduces the dose rate to acceptable levels upon entry.

(2) A device that functions automatically to prevent the use or operation of a radiation source or field while personnel are in the area.

(3) A control device that energizes a conspicuous visible or audible alarm signal so that the individual entering the high-radiation area, and the supervisor of the activity, is made aware of the entry.

(4) Entryways that are locked. During periods when access to the area is required, positive control over each entry is maintained.

(5) Continuous direct or electronic surveillance that is capable of preventing unauthorized entry.

(6) A control device that will automatically generate audible and visual alarm signals to alert personnel in the area before use or operation of the radiation source and in sufficient time to permit evacuation of the area or activation of a secondary control device that will prevent use or operation of the source.

No control(s) shall be established in a high- or very high-radiation area that would prevent rapid evacuation of personnel.

Problems exist when work packages or the job generates a high radiation area, and speical caution and care should be taken to investigate these potential circumstances. Examples include creating a new access into a high-radiation area, opening shielded containers of radioactive material that generates high-radiation fields on opening the container, transfer of radioactive fluids where there is buildup of activity in the system that generates high-radiation fields (e.g., pumping radioactive liquid, salt well pumping, from a single shelled tank to a double shelled tank).

Handling Radioactive Materials

When handling radioactive materials or sources, the level of protection is determined by the exposure rate and the type and degree of contamination. For nonpenetrating radiations, rubber gloves provide protection against alpha and beta radiation, depending on the beta energy. In some cases, multiple pairs of gloves are necessary to provide protection from beta radiation. In cases where high levels of loose contamination are present, multiple pairs of gloves are necessary to prevent the spread of contamination by frequent changing of the outer pair. Depending on the potential for over exposure, workers may frisk for contamination at specified time intervals to mitigate skin doses received. At the end of work the individual should frisk the hands and arms immediately for contamination.

Extention tools are useful when determining the exposure rates of radioactive material. A telescoping detector is also available; in this design, a probe containing two halogen-quenched geiger tubes can be extended up to approximately 14 feet from the user and the readout device. Exposure rates of up to 1,000 R/hr can be recorded while the surveyor's dose is dramatically reduced by utilizing distance. This particular G-M detector has practical applications in several areas: radioactive waste surveys, monitoring irradiated fuel storage and transport, monitoring the removal of irradiated samples from reactors, reducing exposure to personnel when locating and evaluating radioactive sources of unknown strength, and emergency radiation accidents.

If the deep dose exposure rate is high from a small source, then extremity dosimetry may be warranted. Monitoring is required if the extremity dose is greater than 5 rem/yr.

Internal ALARA Controls

Policy

It is the policy of DOE to control internal exposures as low as reasonably achievable (ALARA) by the use of physical design features and administrative controls.

Requirements

The requirements specifying methods to control or prevent internal uptakes are given in 10 CFR 835, Subpart K, Design and Control. Section 835.1001 states:

"The primary methods used shall be physical design features (e.g., confinement, ventilation, and remote handling)."

"Administrative controls and procedural requirements shall be employed only as supplemental methods to control radiation exposure."

In addition, 10 CFR 835, Section 835.1002 states:

> "Regarding the control of airborne radioactive material, the design objective shall be, under normal conditions, to avoid releases to the workplace atmosphere and, in any situation, to control the inhalation of such material by workers to levels that are ALARA; confinement and ventilation shall normally be used."

Administrative Controls

The use of administrative controls to prevent uptakes include the use of procedures and worker training. In order to reduce possible intakes, procedures should specify that routine surveys be taken to identify loose surface contamination, control access to contamination areas by RWP and postings, require workers to monitor upon exiting contaminated areas, establish a policy of prompt decontamination and require worker training on how to contain contamination at the source.

Routine radiological surveys should be performed to detect loose surface contamination. The sooner contamination is detected, the less likely workers will be inadvertently contaminated. Undetected external contamination can lead to inhalation or ingestion of radioactive material.

Contamination control levels and airborne radioactivity areas should be established to prevent inadvertent intakes of radioactive material. A surface should be considered contaminated if either the removable or total radioactivity is detected above 10 CFR 835, Appendix D levels. Surfaces exceeding the Appendix D values for total contamination may be covered with a fixative coating to prevent the spread of contamination. However, reasonable efforts should be made to decontaminate an area before a coating is applied.

Occupied areas, with airborne concentrations of radioactivity that are greater than or potentially greater than, 10 percent of a derived air concentration (DAC) from Appendix A of 10 CFR 835, should be posted as an airborne radioactivity area. For most radionuclides, air containing 10 percent of a DAC results in a committed effective dose equivalent of approximately 10 mrem, if inhaled continuously for one work week.

In addition to posting areas as contaminated or airborne, worker access can be controlled by issuing an RWP. The RWP specifies the training requirements for entry into radiological areas. Workers whose job assignments involve entry to high- and very high-radiation areas, contamination areas, high contamination areas and airborne radioactivity areas must complete Radiological Worker II training. Further, workers who have potential contact with hot particles or use of gloveboxes with high-contamination levels must complete Radiological Worker II training.

According to the *Radiological Control Manual,* Article 221, Personnel Contamination Control, personnel exiting contamination areas, high-contamination areas, airborne radioactivity areas or radiological buffer areas established for contamination control must frisk for contamination as required by the conditions of Article 338, Monitoring for Personnel Contamination. Personnel found with detectable contamination on their skin or personal clothing, other than noble gases or natural background radioactivity, should be promptly decontaminated.

Use of Respirators

The use of respiratory protection devices should be considered as a last resort. The use of engineering and administrative controls to reduce the potential for internal exposure should be evaluated before allowing personnel, with or without respiratory protection, to enter areas with airborne radioactivity.

Loss of Radiological Control

Where loose surface contamination or airborne radioactivity exists, there is the possibility of a potential intake via inhalation and ingestion. Particulate airborne contamination can, over time, plate out and cause loose surface contamination. Conversely, loose surface contamination can cause airborne contamination if agitated.

Surface Contamination

Loose surface contamination is most commonly spread on the soles of shoes and on the palms of hands. Immediate control of the area is necessary to prevent the spread of contamination by workers transgressing the area. A perimeter should be established to control access and egress from the area including the use of radiological postings.

The spread of loose surface contamination depends on the form of the contamination (dry versus wet), the radionuclides involved, and the activity levels. An individual inadvertently walking on dry loose (beta, gamma) surface contamination between 1,000 to 50,000 dpm/100 cm^2 will, in most cases, spread contamination a few feet from the site of origin. As loose surface contamination levels increase above 50,000 dpm/100 cm^2, the spread of contamination becomes more prevalent. In the mrad/hr range, dry surface contamination (beta, gamma) readily goes airborne, migrates on ambient air currents, and spreads quite easily.
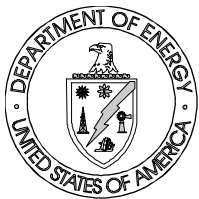
Airborne Contamination

The smaller and dryer the particle, the easier it is for the contamination to go and stay airborne. Particles greater than 10 microns do not stay suspended in air and are generally not respirable. Particle size varies from facility to facility, but most industrial facilities have particle sizes of three to four microns; well within the respirable range.

Once airborne, the contamination can spread, on the air currents, and plate out in clean areas. To prevent this, most facilities have air supplied into clean areas and exhausted from contaminated areas. Air currents created by fans, sweeping, and compressed air cause airborne contamination from dry loose surface contamination. Airborne levels can be kept down by keeping surfaces moist, or by the use of fixatives, but thermally hot surfaces induce evaporation which increases the airborne contamination generated from surface contamination. The use of volatile chemicals on contaminated surfaces can also create airborne problems.

One way to illustrate the hazard from surface contamination going airborne is to compare activity of a one square meter (m^2) area contaminated with plutonium-238 (Pu-238) at levels of 50,000 dpm/100 cm^2 to the stochastic inhalation annual limit on intake (ALI) of 0.01 microcurie (μCi). The dose is:

$$Dose = \frac{100 \ cm \ x \ 100 \ cm}{1} \ \frac{50,000 \ dpm}{100 \ cm^2} \ \frac{1 \mu Ci}{2.22 x 10^6 \ dpm} \ \frac{5 \ rem}{.01 \ \mu Ci} = 1,126 \ rem$$

It can be difficult to calculate the airborne activity as a result of surface contamination and calculations are tenuous at best, but one of the best references is NUREG 1400, *Air Sampling in the Workplace*.

It should be kept in mind that significant doses well in excess of the federal limits can result from a single breath from a dust cloud created from surface contamination. This is particularly true when dealing with alpha-emitting transuranics. The following industry event illustrates the potential:

On March 18, 1996, a manufacturer of gages containing radioactive sources notified the Nuclear Regulatory Commission that an employee was internally contaminated by americium-241 oxide powder. The employee was checking a sealed 10 mCi americium source for leaks when he inhaled the oxide powder. Bioassay results indicated an internal exposure of between 34 and 85 rem committed effective dose equivalent. A 60 rem dose relates to an increase in lifetime cancer mortality risk of 24 in 1,000 or a three percent chance of lung cancer.

Appropriate Personal Protective Equipment (PPE)

Selection of Respiratory Protection

A respirator's purpose is to prevent the inhalation of harmful airborne substances. Functionally, a respirator is designed as an enclosure that covers the nose and mouth or the entire face or head. There are two major classes of respirators: 1) air-purifying respirators (devices that remove contaminants from the air), and 2) atmosphere-supplying respirators (devices that provide clean breathing air from an uncontaminated source).

Regulatory Requirements

Federal regulations, and guidelines (with few exceptions), call for selection and use of respirators that have been tested and certified by the Mine Safety and Health Administration (MSHA) and the National Institute of Occupational Safety and Health (NIOSH).

Selection of Respirators

Respirator selection is a complex process that should be performed by an industrial hygienist or other professional knowledgeable in respiratory protective devices. The individual must be familiar with the limitations associated with each class of respirator, with the actual workplace environment, and with the job task(s) to be performed.

If adequate worker protection is to be achieved, the correct use of the respirator needs to be as important as the selection process. The degree of protection is related, in part, to protection factors. Without a complete respiratory protection program, workers will not receive the degree of protection anticipated from a respirator, even if it is a correct choice for the situation. Training, motivation, medical evaluation, fit testing, and a respirator maintenance program are critical elements for the successful use of a respirator.

Employers should make selection of the proper type(s) of respirators according to the guidance provided in the *American National Standard Practices for Respiratory Protection,* Z88.2-1969 and should be based on the following:
• The nature of the hazardous operation or process
• The type of respiratory hazard including:
  - Physical properties
  - Oxygen deficiency
  - Physiological effects on the body
  - Concentration of toxic material or airborne radioactivity level
  - Established exposure limits of the toxic material

- Established permissible airborne concentration for radioactive material
- Established life or health threatening concentrations for toxic materials

- The location of the hazardous area in relation to the nearest area having respirable air
- The period of time for which respiratory protection must be worn
- The activities of workers in the hazardous area
- The physical characteristics and functional capabilities and limitations of the various types of respirators
- The respirators assigned protection factor

Use of Respirators

Employers should develop standard procedures for respirator use. These procedures should include:

- All information and guidance necessary for proper selection, use, and care of the respirators.
- All possible emergency and routine uses of respirators should be anticipated and planned for.
- A qualified individual supervising the respiratory protective program who must specify the correct respirator for each job. Individual issuing them must be adequately instructed to ensure that they issue the correct respirator.
- Written procedures must be prepared covering the safe use of respirators in dangerous atmospheres that employees might encounter in normal operations or an emergency. Personnel required to wear respirators should be familiar with these procedures and the available respirators.
- Respiratory protection is no better than the respirator in use, even though it is worn conscientiously. Frequent random inspections shall be conducted by a qualified individual to ensure that respirators are properly selected, used, cleaned, and maintained.
- For safe use of any respirator, it is essential that the user be properly instructed in its selection, use, and maintenance. Both supervisors and workers shall be so instructed by competent persons.
- Training shall provide the workers an opportunity to handle the respirator, have it fitted properly, test its face-piece-to-face seal, wear it in normal air for a long familiarity period, and, finally, to wear it in a test atmosphere.

Types of Respirators

The three basic types of respirators are air-purifying, supplied air, and self-contained. Supplied air and self-contained breathing apparatuses are sometimes grouped together as atmospheric-supplying respirators, but are listed separately in this module.

1. Air-Purifying Respirators: These respirators remove air contaminants by filtering, absorbing, or chemical reaction with the contaminants as they pass through the respirator canister or cartridge. These respirators are to be used only where adequate oxygen (19.5 to 23.5 percent by volume) is available. Battery-powered air-purifying respirators are also included in this category. Air-purifying respirators can be classified as follows:

    *   Particulate Filtering Respirators: Used for protection against dusts, fumes, and/or mists.
    *   Gas and Vapor-Removing Respirators: The other major class of airborne contaminants consists of gases and vapors. In contrast to filters, which are effective to some degree no matter what the particulate, the cartridges and canisters used for vapor and gas removal are designed for protection against specific contaminants.

    A Fit test must be performed, and the seal of a respirator must be checked prior to entering a contaminated atmosphere by procedures recommended by the manufacturer or by the following:

    *   Negative Pressure Check. The wearer performs this test by him- or herself in the field. The wearer should use this test just before entering any hazardous atmosphere. It consists of closing off the inlet of the canister, cartridge(s), or filter(s) by covering with the palm(s) or replacing the seal(s), or of squeezing the breathing tube so that it does not pass air; inhaling gently so that the face piece collapses slightly; and holding the breath for 10 seconds. If the face piece remains slightly collapsed and no inward leakage is detected, the respirator is probably tight enough. This test, of course, can be used only on respirators with tight-fitting face pieces.

    *   Positive Pressure Check. This test is very much like the negative pressure check, and it has the same advantages and limitations. It is conducted by closing off the exhalation valve and exhaling gently into the face piece. The fit is considered satisfactory if slight positive pressure can be built up inside the face piece without any evidence of outward leakage. For some respirators, this method requires that the wearer remove the exhalation valve cover and then carefully replace it after the test. The wearer should perform this test just before entering any hazardous atmosphere.

Maintenance, Cleaning, and Inspection. Respirators must be cleaned, disinfected, and stored to properly protect against damage and contamination. OSHA requires that respirators be stored away from dust, sunlight, heat, extreme cold, excessive moisture, damaging chemicals, and mechanical damage.

2. Supplied Air Respirators. These respirators provide breathing air independent of the environment. Such respirators are to be used when the contaminant has insufficient odor, taste, or irritating warning properties, or when the contaminant is of such high concentration or toxicity that an air-purifying respirator would be inadequate. Supplied air respirators, also called air-line respirators, are classified as follows:

    •   Demand - This respirator supplies air to the user on demand (inhalation) which creates a negative pressure within the face piece. Leakage into the face piece may occur if there is a poor seal between the respirator and the user's face.

    •   Pressure Demand - This respirator maintains a continuous positive pressure within the face piece, thus preventing leakage into the face piece.

    •   Continuous Flow - This respirator maintains a continuous flow of air through the face piece and prevents leakage into the face piece.

3. Self-Contained Breathing Apparatus (SCBA). Because the SCBA wearer carries his/her own supply of respirable air, he/she is independent of the surrounding atmosphere. A great advantage of such apparatus is that it allows comparatively free movement over an unlimited area.

    The bulk and weight of most SCBAs make them unsuitable for strenuous work or for use in a constricted space. The limited service life makes them unsuitable for routine use for long continuous periods. The short service life of open circuit type devices may limit them to use where the wearer can go conveniently and quickly from a hazardous atmosphere to a safe atmosphere to change the tank of supply air.

Protection Factors (PFs)

PFs are a very important part of the decision logic system. They are a measure of the overall effectiveness of a respirator. PF numbers have been assigned to an entire class of respirator. The PFs being used by NIOSH are based on quantitative fit tests performed at Los Alamos National Laboratory and elsewhere. Another source of PFs can be found in ANSI Standard Z88.2.

PFs are determined by dividing the ambient airborne concentration outside the mask by the concentration inside the face piece. PFs are used in the selection process to determine the maximum use level (MUL) for the respirator. It is determined by multiplying the permissible exposure limit (PEL) by the PF. If the immediately dangerous to life and health (IDLH) concentration for a specific contaminant is lower than the MUL, the IDLH concentration always takes precedence.

For radiological hazards, selection of respiratory protection will be made on a number of factors including the radionuclide involved, contamination levels, chemical volatility, physical form, area ventilation, and location ventilation, but the main determining factor is the potential internal dose to the workers in the area.

In areas greater than 0.1 DAC, respiratory protection should be evaluated. Engineering controls should be used to reduce airborne radioactivity levels to below 0.1 DAC. Optimization techniques, comparisons of external dose increased due to work slowdown versus internal dose are evaluated to determine respiratory protection requirements when reducing airborne radioactivity below 0.1 DAC is not practicable. Worker comfort is also a factor for consideration in prescribing respiratory protection.

As a general guide the PF of the respirator should exceed the multiple of the DAC concentration. For example if a full face negative pressure respirator has a protection factor of 100 it could be used up to a DAC concentration of 100 as calculated by the following:

$$DAC\ Concentration = \frac{Airborne\ Concentration\ \mu Ci\ ml}{10\ CFR\ 835\ Appendix\ A\ limit\ \mu Ci\ ml}$$

Personal Protective Equipment (PPE)

Take, for example, a spill occurs in a DOE facility containing radioactive materials. A radiological area will be established around the area where the spill occurs. The type of posting may include a contamination area, high-contamination area, and/or airborne radioactivity area. In order not to spread contamination, workers should work from areas of lesser contamination towards areas of higher contamination. To assist in accomplishing this goal, both a contamination area and a high-contamination area may be established next to each other to create a buffer between high-contamination areas and clean areas. Multiple stepoff pads should be used to control the exit from high surface contamination areas. These pads define interim control measures within the posted area to limit the spread of contamination. The following table gives guidance on the use of PPE.

Guidelines for Selecting Protective Clothing (PC)

WORK ACTIVITY	REMOVABLE CONTAMINATION LEVELS		
	LOW (1 to 10 times App. D * values)	MODERATE (10 to 100 times App. D * values)	HIGH (> 100 times App. D * values)
Routine	Full set of PC	Full set of PC	Full set of PC, double gloves, double shoecovers
Heavy work	Full set of PC, work gloves	Double set of PC, work gloves	Double set of PC, work gloves
Work with pressurized or large volume liquids, closed system breach	Full set of non-permeable PC	Double set of PCs (outer set non-permeable), rubber boots	Double set of PC and non-permeable outer clothing, rubber boots

* Appendix D of 10 CFR 835.

In addition to cotton PC, plastic garments are worn over the cotton PC when liquid contamination is present. The plastic suits are generally discarded after use.

Exposure Rate Calculations

The intensity of the radiation field decreases as the distance from the source increases. Therefore, increasing the distance will reduce the amount of exposure received. The decrease of exposure rate with distance is very dependent on the type of geometry. There are three types of geometries commonly encountered in the field: point sources, line sources, and plane sources. Each of these geometries use a different formula to calculate exposure rate.

Point Sources

The intensity of the radiation field decreases as the distance from the source increases. Therefore, increasing the distance will reduce the amount of exposure received. In many cases, especially when working with point sources, increasing the distance from the source is more effective than decreasing the time spent in the radiation field.

Theoretically, a point source is an imaginary point in space from which all the radiation is assumed to be emanating. While this kind of source is not real (all real sources have dimensions), any geometrically small source of radiation behaves as a point source when one is within three times the largest dimension of the source. Radiation from a source is emitted equally in all directions. Thus, the photons spread out to cover a greater area as the distance from the point source increases. The effect is analogous to the way light spreads out as we move away from a single source of light, such as a light bulb.

The radiation intensity for a point source decreases according to the **Inverse Square Law** which states that as the distance from a point source decreases, or increases, the dose rate increases, or decreases, by the square of the ratio of the distances from the source. The inverse square law becomes inaccurate close to the source (i.e., within three times the largest dimension of the source). For an example on how to perform a point source calculation, see Section 3 of this competency.

As previously mentioned, the exposure rate is inversely proportional to the square of the distance from the source. The mathematical equation is:

$$I_1(d_1)^2 \ = \ I_2(d_2)^2$$

where: I_1 =   exposure rate at 1st distance (d_1)
I_2 =   exposure rate at 2nd distance (d_2)
d_1 = 1st (known) distance
d_2 = 2nd (known) distance

- Assuming the attenuation of the radiation in the intervening space is negligible.
- Assuming the dimensions of the source and the detector are small compared with the distance between them.

The inverse square law holds true only for point sources; however, it gives a good approximation when the source dimensions are smaller than the distance from the source to the exposure point. Due to distance constraints, exposures at certain distances from some sources, such as for a pipe or tank, cannot be treated as a point source. In these situations, these sources must be treated as line sources or large surface sources.

Line Source

Not all radiation sources are point sources. Pipes, storage tanks, and other components must be considered to make better approximations for adequate radiation protection. A line source is a source of radiation where the longest dimension of the source is used for calculations. The formula for a line source is:

$$X = \frac{\Gamma \, C_L}{r} \left(\tan^{-1} \frac{L_1}{r} + \tan^{-1} \frac{L_2}{r} \right)$$

where: X = the exposure rate in R hr^{-1}
L_1 = the length of line segment L_1
L_2 = the length of line segment L_2
C_L = activity per unit length
r = distance from line
Γ = specific gamma constant

NOTE: $\tan^{-1}$ is in radians

Plane Source

Planar, or surface, sources of radiation can be the floor or wall of a room, a large cylindrical or rectangular tank, or any other type of geometry where the width or diameter is not small compared to the length. Accurate calculations for these types of sources require the use of calculus; however, a relationship can be described for how exposure rate varies with distance from the source using the following equation:

$$X = \pi \, C_a \, \Gamma \, \ln \left(\frac{L^2 + R^2}{R^2} \right)$$

where: X = the exposure rate in R hr^{-1}
C_a = activity per unit area
L = radius of the source surface
R = the distance from the source
Γ = specific gamma constant
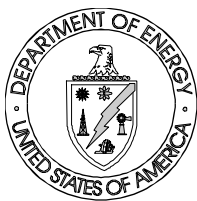
Shielding Calculations

Gamma photon absorption is an exponential process. Theoretically, this means that gamma photons are never completely stopped, no matter how thick the absorber. However, we can choose a shield thickness that will reduce the intensity to acceptable levels. The following formula can be used for calculating gamma shield thickness:

$$I = I_o e^{-\mu x}$$

where: I = desired radiation intensity (mrem/hr)
I_o = initial radiation intensity (mrem/hr)
μ = total linear attenuation coefficient (cm^{-1})
x = shield thickness (cm)

The first formula is used for narrow beam conditions. Here, it is assumed that all the gamma photons that interact are removed from the beam. If this equation is used in treating a wide beam of radiation, the required shield thickness will be underestimated due to compton scattered photons. To avoid underestimating the shield thickness, a buildup factor is used. The formula is:

$$I = I_o B e^{-\mu x}$$

where: I = desired radiation intensity (mrem/hr)
I_o = initial radiation intensity (mrem/hr)
μ = total linear attenuation coefficient (cm^{-1})
x = shield thickness (cm)
B = buildup factor

Knowing the buildup factor the true gamma flux can be calculated. This gives a more accurate value for the needed shield thickness.

<u>Half-Value Layer (HVL)</u>

The simplest method for determining the effectiveness of the shielding material is using the HVL concept. One HVL is defined as the amount of shielding material required to reduce the radiation intensity to one-half of the unshielded value. The HVLs of various materials and photon energies are given in the following table.

Half-Value Layers

Photon Energy (keV)	HVL (cm)			
	Lead (11.35 g/cm³)	Iron (7.86 g/cm³)	Concrete (2.4 g/cm³)	Water (1.0 g/cm³)
500	0.38	1.0	3.3	7.2
1,000	0.86	1.5	4.5	9.8
1,500	1.2	1.8	5.6	12.0
2,000	1.3	2.1	6.4	14.0
3,000	1.5	2.4	7.9	17.5

As can be seen from the chart above,` HVLs are energy and material dependant. There is another variable that affects the shielding, and that is density of the material. All of these factors are accounted for in the total linear attenuation coefficient given earlier. The linear attenuation coefficient, μ, is obtained from standard tables for various shielding materials and is related to the HVL by the following formula:

$$HVL = \frac{\ln 2}{\mu} = \frac{0.693}{\mu}$$

Buildup Factors

Not all gamma photons that pass through shielding material are attenuated. Some of them pass completely through the shield as uncollided gamma flux. Others interact with the atoms in the shield by compton scattering, producing lower energy scatter photons. The buildup factor accounts for the compton scattered photons that are coming through the shield and interacting with the detector. The value of the buildup factor varies with the radiation energy, shield material, source geometry, and depth of shield penetration. Tables of buildup factors for a variety of shielding materials, such as water, concrete, and iron can all be found in the *Radiological Health Handbook*.

The quantity, μx, is called the **relaxation length**, which is the thickness of absorber needed for a reduction of 1/e in the initial beam intensity. To determine the value for B from the tables, the relaxtion length, pertaining to the specific problem, must be calculated. The following gives buildup factors for a point source in lead.

Dose Buildup Factors for a Point Isotropic Source in Lead							
	μx						
MeV	1	2	4	7	10	15	20
0.5	1.24	1.42	1.69	2.00	2.27	2.65	2.73
1.0	1.37	1.69	2.26	3.02	3.74	4.81	5.86
2.0	1.39	1.76	2.51	3.66	4.84	6.87	9.00
3.0	1.34	1.68	2.43	2.75	5.3	8.44	12.3

For examples of how to perform shielding calculations, see Section 3 of this competency.

3. SELF-STUDY SCENARIOS/ACTIVITIES AND SOLUTIONS

Activity 1

What is the exposure rate one foot from an unshielded cobalt-60 source which contains 72 curies of activity?

Activity 2 (No buildup factors)

How much lead shielding is required to reduce the intensity of a 1.0 MeV gamma photon from 475 rem/hr to 5 mrem/hr?

$$I = I_o e^{-\mu x}$$

where: I = desired radiation intensity (mrem/hr)
         I_o = initial radiation intensity (mrem/hr)
         μ = total linear attenuation coefficient (cm^{-1})
         x = shield thickness (cm)

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Activity 3, (Use of buildup factors)

How much lead shielding is required to reduce the intensity of a 3.0 MeV gamma photon from 1,800 rem/hr to 25 mrem/hr, taking into account the buildup factor?

$$I = I_o B e^{-\mu x}$$

where: I = desired radiation intensity (mrem/hr)
I_o = initial radiation intensity (mrem/hr)
μ = total linear attenuation coefficient (cm^{-1})
x = shield thickness (cm)
B = buildup factor

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Activity Solutions:

Activity 1, Solution

Before the problem can be solved, the value of E, the average energy per disintegration, must be determined.

Cobalt-60 emits two photons every time a disintegration takes place. Their energies are 1.17 and 1.33 MeV. When two or more photons are emitted at the same time, the average energy may be used in the equation and multiplied by the number of gamma photons per disintegration or the sum of the energies may be used for the product of E and N:

$$E \times N = [1.17 \text{ MeV} \times 100\%] + [1.33 \text{ MeV} \times 100\%] = 2.5 \text{ MeV}$$

The problem can now be solved by substituting the values of C and E into the equation:

$$X = \frac{(6)\ (72\ Ci)\ (2.5\ MeV)}{1^2} = 1{,}080\ R/hr$$

Activity 2, Solution

Solve the equation for *x* by the following steps:
1. Divide both sides by I_o
2. Take the natural log of both sides
3. Divide both sides by -μ

$$x = \frac{\ln\left(\dfrac{I}{I_o}\right)}{-\mu}$$

Obtain the HVL from the chart, substitute numbers, and solve:

$$x = \frac{\ln\left(\dfrac{5\ mrem}{475{,}000\ mrem}\right)}{\left(\dfrac{-.693}{.86\ cm}\right)} = \frac{-11.46}{-.8058\ cm^{-1}} = 14.22\ cm$$

Activity 3, Solution

Solve the equation for *x*, by the following steps:

1. Divide both sides by I_o
2. Take the natural log of both sides
3. Divide both sides by -μ
4. After calculating *x* multiply by μ to obtain the number of relaxation lengths
5. Cross reference the μ*x* with the buildup factor
6. Solve the formula again using the buildup factor

$$x = \frac{\ln\left(\frac{I}{I_o}\right)}{-\mu}$$

Obtain the HVL from the chart, substitute numbers, and solve for *x*:

$$x = \frac{\ln\left(\frac{25 \ mrem}{1,800,000 \ mrem}\right)}{\left(\frac{-.693}{1.5 \ cm}\right)} = \frac{-11.18}{-.462 \ cm^{-1}} = 24.2 \ cm$$

Calculate the relaxation lengths:

$$relaxation \ lengths = \frac{-.693}{1.5 \ cm} \ \frac{24.2 \ cm}{1} = -11.18$$

Interpolate the buildup factor:

$$Buildup = \left(\frac{8.44 - 5.3}{5}\right) + 5.3 = 5.9$$

Substitute the build up factor back into the formula and solve

$$x = \frac{\ln\left(\dfrac{25\ mrem}{(5.9)\ (1,800,000\ mrem)}\right)}{\left(\dfrac{-.693}{1.5\ cm}\right)} = \frac{-12.95}{-.462\ cm^{-1}} = 28\ cm\ of\ lead$$

4. SUGGESTED ADDITIONAL READINGS AND/OR COURSES

Readings

- 10 CFR 835, *Occupational Radiation Protection.*
- DOE N 441.1, *Radiological Protection for DOE Activities.*
- DOE/EH-0256T (Revision 1), *Radiological Control Manual*
  NOTE: See Appendix 3A, Checklist for Reducing Occupational Radiation Exposure, pp. 3-35 & 3-36.
- DOE Order 5480.4, *Environmental Protection, Safety, and Health Protection Standards.*
- G-10 CFR 835, Revision 1, *Implementation Guides for Use with Title 10 Code of Federal Regulations 835.*
- International Commission on Radiological Protection. *Cost-Benefit Analysis in the Optimization of Radiation Protection (ICRP 37).* New York: Author.
- International Commission on Radiological Protection. *Recommendations on the International Commission of Radiological Protection (ICRP 60).* New York: Author.
- Pacific Northwest Laboratory. (1988). *Department of Energy Health Physics Manual of Good Practices for Reducing Radiation Exposure to Levels that are As Low As Reasonably Achievable (ALARA)* (PNL-6577). Richland, WA: Author.
- NUREG 1400. *Air Sampling in the Workplace.*
- Shleien, B., *Radiological Health Handbook (*Revised Edition*),* Scinta, inc., 1992.

Courses

- DOE/EH-0450 (Revision 0), *Radiological Assessors Training (for Auditors and Inspectors) - Fundamental Radiological Control,* sponsored by the Office of Defense Programs, DOE.
- *Applied Health Physics* -- Oak Ridge Institute for Science and Education.
- *Health Physics for the Industrial Hygienist* -- Oak Ridge Institute for Science and Education.
- *Safe Use of Radionuclides* -- Oak Ridge Institute for Science and Education.
- *Radiation Protection Functional Area Qualification Standard* -- GTS Duratek.